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# Developmental History of Soil Concepts from a Scientific Perspective

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**Featured Application: New concepts within the soil science community have emerged through multiple actions: (1) reflection on the social, cultural, and/or political needs that exist outside the soil science community, and (2) by being progressive and relevant to new emergent interests (e.g., health and security). Future applications of research communication are expanding from traditional formats (e.g., papers, books, printed journals) to digital research platforms that enhance the capacity of growth in soil science research.**

**Abstract:** Various soil concepts have emerged since the beginning of the twentieth century, with some shared similarities. These concepts have contributed to a rise in the awareness of protecting limited soil resources, but not every idea has equally gained widespread attention from scientists. The purpose of this study was to document the developmental history of 10 soil concepts from 1900 to 2018 and investigate their growth/decline. Articles containing words related to the selected soil concepts in titles, abstracts, or publication contents available in the Web of Science were examined. "Soil production" was the oldest concept, found in a paper published in 1910, followed chronologically in the literature by soil care, fertility, conservation, quality, health, protection, security, sustainability, and resilience. Most of the concepts were initially found in non-soil-science journals that predated publications in soil science journals, which implies slowness of the soil science community's adoption. The statistical publication trend for each concept over time was analyzed and interpreted based on diffusion of innovation theory. The results suggest that all of the soil concepts experienced a statistically positive/upward shift ($p < 0.01$) over time. In particular, soil concepts cited in soil science journals tended to maintain their momentum and communal value over time in soil science research, except the soil care concept. Applications of soil concept research based on collaboration between scientists of different nationalities, affiliations, and research expertise would further increase the possibility of citation frequency and foster interdisciplinary and transdisciplinary collaboration.

**Keywords:** soil health; soil quality; soil security; soil conservation; soil fertility; soil sustainability; soil productivity; soil care; soil protection; soil resilience



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## 1. Introduction

Various soil concepts have been discussed over time in the soil science community, and narrative descriptions of these concepts have been developed to capture the increasing complexity of soil–environmental issues. Many of these have helped to raise awareness of the need to protect limited soil resources [1], but some are used inconsistently or interchangeably due to the shared semantics of their definitions, aims, and/or scopes [2]. Soil quality and soil health are examples of concepts that improve public awareness of the importance of soil resources, with short- and long-term soil management that influence soil functions and processes in practice [3,4].

Soil concepts seem to arise from a combination of various pathways: researchers in the scientific community (top-down); dialogue in professional organizations (top-down and bottom-up); and communication with stakeholders (bottom-up). Mizuta et al. (2018) summarized diverse definitions of soil concepts, including soil quality, soil health, and soil security [2]. These definitions were proposed by scientists and professional organizations, such as the Soil Science Society of America (SSSA). Semantic similarities can be found among the definitions of each soil concept. Soil quality and soil health are used loosely and interchangeably with another soil concept, soil fertility [5]. Stevens explained soil health as a holistic measure of soil productivity, resilience, and sustainability [6]. Soil care has been promoted, along with soil productivity and fertility, in the service of farmers [7]. Soil care can be seen as a broad concept encompassing soil fertility, soil conservations, and/or protection from soil degradation [8].

Professional institutions seem to play the role of aggregating individual proposed ideas into an adaptable form for various stakeholders. On the other hand, Sojka et al. (2003) sounded an alert in regard to the impacts of institutionalizing definitions of soil concepts that may prevent specific stakeholders from protecting/managing soil resources properly [9]. The gap between individual and collective perceptions/perspectives must be revealed and closed. For instance, Grunwald et al. (2017) addressed this need using the Meta Soil Model, which is rooted in integral theory and integral ecology [10]. Bouma (2011) asserted that the different opinions of various stakeholders (farmers, non-governmental organizers, manufacturers, researchers, etc.) and policymakers must be aligned to enable successful projects based on a review of sustainability problems in Dutch agriculture [11]. Ng and Zhang (2019) stated that top-down policy-driven changes in soil health management will be necessary for the common good [5]. However, the bottom-up approach is underappreciated in current soil concepts.

Understanding how soil concepts have evolved in the soil science community is crucial for soil scientists, because the concepts' backgrounds may reflect social, cultural, and/or political needs and events/situations. In addition, quantitative trend analysis of soil concepts over time can reveal how each concept has gained attention and been popularized through scientific research.

Thus, the purpose of this study is to quantitatively understand the developmental history of various soil concepts (1900 to 2018) and demonstrate changes in their frequency of use over time. Identifying the origins of each soil concept in publications for the first time may provide insights into how the soil science community adopts new ideas in scientific research.

## 2. Materials and Methods

### *2.1. Searching Soil Concept Publications in the Web of Science*

Ten major soil concepts were selected for investigation: soil productivity, care, fertility, conservation, protection, sustainability, resilience, quality, health, and security (Table 1). The number of publications that contain each concept available in the Web of Science was analyzed. Materials published from 1900 to 2018 were retrieved on 29 July 2019. The "all languages" setting was used in the retrieval process, with 52 different languages available on the website. Search keys for the analysis were imputed with the wildcard character, asterisk (*), as right-hand truncation and quotation marks (Table 1). Though the wildcard works for searched items in English only and turns off the automatic lemmatization function and internal synonym finder, this process identified exact phrases and variant spellings of a word. The following document types were selected for the search: article, editorial material, book, book chapter, letter, note, proceedings paper, and review. Each category is described in the Web of Science Core Collection Help section (accessed on 30 July 2019: http://images.webofknowledge.com). The text areas searched for the selected soil concepts in the published materials were limited to titles, abstracts, and key words. This process was expected to minimize the risk of retrieving records that used a given soil concept term in contexts that differed from its conceptual definition.

**Table 1.** Search keys for each soil concept (in English).

| Soil Concepts | Search Keys |
|---|---|
| Soil Care | "Soil care*" |
| Soil Conservation | "Soil conservat*" |
| Soil Fertility | "Soil fertilit*" |
| Soil Health | "Soil health*" |
| Soil Productivity | "Soil productiv*" |
| Soil Protection | "Soil protect*" |
| Soil Quality | "Soil qualit*" |
| Soil Resilience | "Soil resilien*" |
| Soil Security | "Soil securit*" |
| Soil Sustainability | "Soil sustainabilit*" |

Note that the asterisk (*) is the wildcard that represents any group of characters, including no character.

Two groups, soil science journals and "all" (i.e., both soil science and non-soil science) journals, were searched to identify pioneering contributions from scientists across the research fields. A total of 35 soil science journals exclusively within the soil science category were examined to analyze the number of publications containing each soil concept. Of the 35 soil science journals, the earliest publication was the *Soil Science* (SS) journal in 1916, and the most recent was *Geoderma Regional* in 2016. Journals without an impact factor were considered in identifying pioneer contributors for each concept but not in the trend analyses. The annual impact factor (IF) for year 2018 is automatically generated on the website with the equation:

$$\mathrm{IF} = X/Y \quad (1)$$

where $X$ is the number of 2018 citations and $Y$ is the number of source publications published during the previous two years (2016–2017). The IF measures citations of published articles divided by the number of recent articles and represents the significance of citation frequency by eliminating biases such as the size of the journal, issue frequency, and citable body size of the literature [12]. The calculation of eigenfactor scores (ES), on the other hand, is based on the number of times articles from the journal published in the past five years are cited and excludes self-citations from the calculation. The metrics are calculated using network analysis to determine the mathematical weights and apply them to each citation depending on the citation influence of the source publication [12]. Total numbers of publications for soil concepts in soil science journals and all journals were calculated to understand the contribution from the soil science community for each soil concept. The earliest publications with soil concepts were also retrieved from the Web of Science database.

### 2.2. Statistical Methods for Change Point Detection and Trend Analysis of Publications

A single change point, at which the number of publications for each soil concept significantly increases/decreases during the search period (1900–2018), was identified using a nonparametric method, Pettitt's test [13]. This point represents abrupt changes in the data when a property of the time series shifts. In other words, statistical distributions would likely differ for past and future data at that point. This analysis does not assume that $Y_i$ values (number of publications over time in our case) are normally distributed, because the algorithm is based on the ranks of the elements of a series rather than on the values themselves [14]. Thus, it is less sensitive to outliers. The analysis was conducted using the "trend" package in R (3.5.3) [15].

A nonparametric trend analysis, the Mann–Kendall test, was also performed to assess whether there is a statistical upward/downward trend in the number of publications separately for each soil concept over time. This rank-based analysis does not assume that the $Y_i$ values conform to any unique distributions [16]. The algorithm computes the difference between the later-measured value and all earlier-measured values to identify positive/negative differences or no differences [17]. Hirsch et al. (1982) described this method as appropriate for quantifying the large magnitude of changes over time [18]. The analysis was conducted using the "Kendall" package in R [19].

## 3. Results

A total of 35 journals were grouped in the soil science category in the Web of Science (Table 2). The youngest journal with over 10,000 total citations was *Catena*, which began publishing in 1983. No journals published within the past decade have yet reached 2000 citations. A few journals published before 2015 have not reached more than 1000 citations, such as *Agrochimica*, *Arid Land Research and Management*, and *Soil and Water Research*.

**Table 2.** List of soil science journals found in Web of Science on 27 July 2019.

| Journal Title | Year of First Publication | Total Citations [1] | Impact Factor (2018) | Eigenfactor Score (×1000) |
|---|---|---|---|---|
| *Soil Science (SS)* | 1916 | 7053 | 1.70 | 1.18 |
| *Plant and Soil* | 1948 | 33,620 | 3.26 | 23.64 |
| *Agrochimica* | 1965 | 221 | 0.65 | 0.16 |
| *Canadian Journal of Soil Science* | 1965 | 3130 | 0.95 | 1.37 |
| *Pedobiologia* | 1965 | 2480 | 1.83 | 1.20 |
| *Journal of Soil and Water Conservation (JSWC)* | 1967 | 4171 | 2.18 | 3.03 |
| *Clays and Clay Minerals (CCM)* | 1968 | 5550 | 1.84 | 1.22 |
| *Geoderma* | 1968 | 23,042 | 4.34 | 21.89 |
| *Soil Science Society of America Journal (SSSAJ)* | 1972 | 24,121 | 2.00 | 7.28 |
| *Communications in Soil Science and Plant Analysis (CSSPA)* | 1974 | 5644 | 0.69 | 2.69 |
| *Soil Biology & Biochemistry (SBB)* | 1974 | 36,977 | 5.29 | 31.75 |
| *Soil Science and Plant Nutrition* | 1976 | 3205 | 1.42 | 1.93 |
| *Soil & Tillage Research (STR)* | 1980 | 12,573 | 4.68 | 10.33 |
| *Catena* | 1983 | 13,025 | 3.85 | 16.62 |
| *Biology and Fertility of Soils (BFS)* | 1985 | 8837 | 4.83 | 6.39 |
| *Soil Use and Management* | 1986 | 2958 | 1.96 | 2.13 |
| *Acta Agriculturae Scandinavica Section B-Soil and Plant Science* | 1992 | 1070 | 0.81 | 1.17 |
| *Eurasian Soil Science* | 1992 | 1783 | 0.88 | 1.11 |
| *European Journal of Soil Biology* | 1993 | 3139 | 2.24 | 3.18 |
| *Applied Soil Ecology* | 1994 | 9096 | 3.45 | 10.78 |
| *European Journal of Soil Science* | 1994 | 7014 | 2.82 | 4.94 |
| *Compost Science & Utilization* | 1995 | 757 | 1.00 | 0.27 |
| *Land Degradation & Development (LDD)* | 1996 | 5333 | 4.28 | 6.94 |
| *Nutrient Cycling in Agroecosystems* | 1996 | 4344 | 2.85 | 2.86 |
| *Journal of Plant Nutrition and Soil Science* | 1999 | 4564 | 2.06 | 3.68 |
| *Arid Land Research and Management* | 2001 | 518 | 0.99 | 0.53 |
| *Vadose Zone Journal (VZJ)* | 2002 | 4450 | 3.63 | 5.00 |
| *Pedosphere* | 2003 | 2896 | 3.19 | 3.22 |
| *Revista Brasileira De Ciencia Do Solo* | 2003 | 3553 | 1.17 | 2.54 |
| *Journal of Soils and Sediments (JSS)* | 2005 | 5572 | 2.67 | 8.44 |
| *Journal of Soil Science and Plant Nutrition* | 2010 | 1440 | 2.01 | 2.01 |
| *Soil and Water Research* | 2010 | 318 | 1.21 | 0.46 |
| *Archives of Agronomy and Soil Science* | 2011 | 1605 | 1.68 | 2.73 |
| *Soil Research* | 2011 | 1110 | 1.57 | 2.29 |
| *Geoderma Regional* | 2016 | 311 | 1.50 | 0.91 |

[1] Total number of times each journal has been cited by all journals included in the database from the time when the journal began publishing.

The following journals were ranked as having the five highest IF and ES scores: *Soil Biology & Biochemistry* (SBB); *Biology and Fertility of Soils* (BFS); *Soil & Tillage Research* (STR); *Geoderma; and Land Degradation & Development* (LDD). Both the *Vadose Zone Journal* (VZJ) and *Pedosphere* (PDP), which began publishing within the past decade, ranked in the top 10 in terms of IF but not for ES. On the other hand, the *Journal of Soils and Sediments* (JSS) and the *Soil Science Society of America Journal* (SSSAJ) ranked within the top 10 for ES.

In some cases, journals were ranked higher for IF and/or ES with fewer total citations. For example, *Clays and Clay Minerals* (CCM) from 1968 and LDD from 1996 were similar in terms of total citations, but the IF of CCM was nearly two times higher than that of LDD. Even journals with fewer total citations, such as PDP, received higher IF and ES scores than CCM. *Communications in Soil Science and Plant Analysis* (CSSPA), which received a similar number of total citations as CMM, had a higher ES score but only half the IF score of CMM. The ES score of the JSS was notably high, considering that its total citations were similar to those for CCM.

### 3.1. Scientific Attention to Soil Concepts in All-Category Journals and Soil Science Journals

The number of publications from all-category journals (i.e., both soil and non-soil science, labelled "all journals" hereafter) and soil science journals was derived for each soil concept (Table 3). Soil fertility and soil quality received great attention in both all journals and soil science journals, followed by soil conservation and soil health. Soil productivity and soil resilience concepts appeared in soil science journals relatively more often than the other concepts, at more than 36%. The rates of publications found in soil science journals out of those in all journals ranged from 25% to 54%, with most rates under 40%.

**Table 3.** Number of publications using soil concepts in all journals and soil science journals.

| Soil Concepts | All | Soil Science | (%) |
|---|---|---|---|
| Soil Fertility | 12,498 | 3064 | (24.52) |
| Soil Quality | 8029 | 2846 | (35.45) |
| Soil Conservation | 3554 | 883 | (24.85) |
| Soil Health | 1657 | 459 | (27.70) |
| Soil Productivity | 1318 | 483 | (36.65) |
| Soil Protection | 793 | 210 | (26.48) |
| Soil Sustainability | 166 | 57 | (34.34) |
| Soil Resilience | 119 | 64 | (53.78) |
| Soil Security | 33 | 15 | (45.45) |
| Soil Care | 21 | 6 | (28.57) |

### 3.2. Early Studies of Soil Concepts

The earliest soil concept publications were identified in all journals and soil science journals available in the Web of Science. In all journals, soil fertility was the earliest concept published in a journal (1908), followed chronologically in the literature by soil productivity, conservation, quality, health, protection, care, security, sustainability, and resilience (Table 4). Soil quality was examined in one article written in German; all the other materials were written in English. Interestingly, the earliest article on soil health was found in a medical journal (Table 4). Soil sustainability and soil resilience were the only concepts that, on the first occasion, were published in soil science journals.

When the search window was limited to soil science journals, the order of first appearance for some soil concepts was different from the order for all journals (Table 5). The earliest literature for soil fertility was found in 1917, which was nine years after the article was published in a non-soil-science journal. Ten authors were identified for early studies of soil conservation. The authors (H.H. Bennett, A.L. Patrick, T.S. Buie, R.H. Musser, L.P. Merrill, A.E. Mccymonds, C. Luker, C., and J.H. Christ) published their article in 1947 in the same issue of *Soil Science Journal* (SSJ, volume 64, issue 6). The author who published the first articles about soil resilience in the category 'all journal' and soil science journals was R. Lal [20]. The soil quality concept appeared for the first time in an article in the *Soviet Soil Science-USSR* (SSS-USSR) in 1971.

**Table 4.** Search results for soil concepts found in articles in all (soil and non-soil science) journals (1900 to 2018) available at Web of Science.

| Soil Concepts | Year | Author | Title of Published Article | Name of Journal | Volume | Issue | Pages |
|---|---|---|---|---|---|---|---|
| Soil Fertility | 1908 | Schreiner, O. and Shorey, E.C. | The isolation of picoline carboxylic acid from soils and its relation to soil fertility | *Journal of the American Chemical Society* | 30 | 8 | 1295–1307 |
| Soil Productivity | 1910 | Russell, E.J. | The Effect of Earthworms on Soil Productiveness | *Journal of Agricultural Science* | 3 | | 246–257 |
| Soil Conservation | 1926 | Lipman, J.G. | Future Trends in Soil Conservation | *Industrial and Engineering Chemistry* | 18 | | 1034–1040 |
| Soil Quality | 1939 | Wolff, W. | Die bodenkundlichen Grundlagen der deutschen Reichs-Bodenschätzung (The science of soil basis of German soil quality evaluation) | *Naturwissenschaften* | 27 | | 374–376 |
| Soil Health | 1951 | Forman, J. | Soil, Health, and the Dental Profession | *Journal of Prosthetic Dentistry* | 1 | 5 | 508–522 |
| Soil Protection | 1953 | Tabor, P. | Crabgrass for Soil Protection and Forage | *Agronomy Journal* | 45 | 3 | 123–123 |
| Soil Care | 1972 | Anonymous | Soil Care | *Agriculture Journal* | 79 | 12 | 549–550 |
| Soil Security | 1985 | Tadanier, R. and Ingles, O.G. | Soil Security Test for Water Retaining Structures | *Journal of Geotechnical Engineering-ASCE* | 111 | 3 | 289–301 |
| Soil Sustainability | 1992 | Friend, J.A. | Achieving Soil Sustainability | *Journal of Soil and Water Conservation* | 47 | 2 | 156–157 |
| Soil Resilience | 1993 | Lal, R. | Tillage Effects on Soil Degradation, Soil Resilience, Soil Quality, and Sustainability-Introduction | *Soil & Tillage Research* | 27 | 1–4 | 1–8 |

**Table 5.** Search results of soil concepts in soil science journal articles (1900 to 2017), Web of Science.

| Soil Concepts | Year | Author | Titles | Name of Journal | Volume | Issue | Pages |
|---|---|---|---|---|---|---|---|
| Soil Fertility | 1917 | Gainey, P. L. | The Significance of Nitrification as a Factor in Soil Fertility | *Communications in Soil Science and Plant Analysis* | 3 | 5 | 399–416 |
| Soil Conservation | 1947 | Bennett, H. H.; Patrick, A. L.; Buie, T. S; Musser, R. H.; Merrill, L.P.; Mccymonds, A.E.; Luker, C.; Christ, J.H. [1] | Development of Our National Program of Soil Conservation and Good Land Use in the United States | *Soil Science* | 64 | 4 | 259–364 |
| Soil Productivity | 1948 | Hopp, H. and Slate, C.S. | Influence of Earthworms on Soil Productivity | *Soil Science* | 66 | 6 | 421–428 |
| Soil Quality | 1971 | Taychinov, S.N. | A Method for Rating Soil Quality | *Soviet Soil Science-USSR* | 3 | 1 | 40-+ |
| Soil Protection | 1974 | Braley, N.D.; Smith, D.A. | Soil Protection for Spud Production | *Soil Conservation* | 39 | 11 | 14–16 |
| Soil Sustainability | 1992 | Friend, J.A. | Achieving Soil Sustainability | *Journal of Soil and Water Conservation* | 47 | 2 | 156–157 |
| Soil Health | 1992 | Haberern, J. | A Soil Health Index | *Journal of Soil and Water Conservation* | 47 | 1 | 6–6 |
| Soil Resilience | 1993 | Lal, R. | Tillage Effects on Soil Degradation, Soil Resilience, Soil Quality, and Sustainability-Introduction | *Soil & Tillage Research* | 27 | 1-4 | 1–8 |
| Soil Care | 1994 | Wallace, A. S. | Soil Care and The USA National Debts | *Communications in Soil Science and Plant Analysis* | 25 | 1-2 | 153–157 |
| Soil Security | 2013 | Bouma, J. and McBratney, A. | Framing Soils as an Actor When Dealing with Wicked Environmental Problems | *Geoderma* | 200 | | 130–139 |

[1] Seven authors published articles in a journal in the same volume and issue, which investigated the different regions of the United States. Each title was listed in the order of authors in this table: Development of Our National Program of Soil Conservation; Soil Conservation and Good Land Use in the Northeastern Region; Soil Conservation and Good Land Use in the Southeastern Region; Soil Conservation and Good Land Use in the Upper Mississippi Region; Soil Conservation and Good Land Use in the Western Gulf Region; Soil Conservation and Good Land Use in the Northern Great Plains Region; Soil Conservation and Good Land Use in the Southwestern Region; Soil Conservation and Good Land Use in the Pacific Region.

Several soil science journals published pioneering work for different soil concepts (Table 5). For example, CSSPA recorded the earliest articles for soil fertility and soil care; SSJ produced the earliest articles on soil conservation and soil productivity concepts; and the *Journal of Soil and Water Conservation* (JSWC) produced the earliest work on soil sustainability and soil health. These journals appeared before 1974 and can be classified as relatively old journals for soil concepts.

### 3.3. Quantitative Trends in Soil Concepts

Soil concepts were introduced and popularized at different times. Pettitt's test was conducted to find the change point in the number of publications for soil concepts over time (Table 6). The test shows that all soil concepts, except for soil care and soil security, experienced statistically significant shifts in the number of citations between 1900 and 2018.

**Table 6.** Statistics summary of Pettitt's test and Mann–Kendall test for soil concepts.

| Soil Concepts | Pettitt's Test | | | Mann–Kendall Test | | |
|---|---|---|---|---|---|---|
| | U Statistics | *p*-Value | Change Point (Year) | Kendall Score | Kendall's Tau Statistic | *p*-Value |
| Soil Conservation | 3296 | <0.01 | 1967 | 4437 | 0.77 | <0.01 |
| Soil Fertility | 3203 | <0.01 | 1971 | 4462 | 0.70 | <0.01 |
| Soil Quality | 2676 | <0.01 | 1979 | 3423 | 0.69 | <0.01 |
| Soil Productivity | 2943 | <0.01 | 1981 | 3867 | 0.70 | <0.01 |
| Soil Protection | 2548 | <0.01 | 1991 | 3039 | 0.64 | <0.01 |
| Soil Sustainability | 1840 | <0.01 | 1992 | 2013 | 0.52 | <0.01 |
| Soil Health | 2208 | <0.01 | 1992 | 2478 | 0.59 | <0.01 |
| Soil Resilience | 1953 | <0.01 | 1993 | 2058 | 0.52 | <0.01 |
| Soil Care | 564 | 0.65 | 1994 | 540 | 0.25 | <0.01 |
| Soil Security | 678 | 0.39 | 2013 | 680 | 0.31 | <0.01 |

Results from the Mann–Kendall test showed that all soil concepts had positive tau values ($p < 0.00$), indicating that the trend of citing the soil concepts overall has statistically increased. Soil care and soil security did not observe a statistically significant change point ($p > 0.05$). A possible reason could be the low number of publications found in the literature analysis. We found that soil care did appear in published articles at low frequency, but more prominently on websites. Soil security was introduced in soil science journals more recently, which is likely the reason that it had the lowest frequency of citations.

The differences between the year when each soil concept appeared for the first time in all journals (A) and the soil science journals (B) and the change points (C) were calculated in detail (Table 7). Many soil concepts appeared in soil science journals 20 years or more after they appeared in non-soil-science journals for the first time (B-A in Table 7). Soil fertility was an exception, with a nine-year difference. Soil resilience and soil sustainability concepts had a value of zero because they appeared in soil science journals first. Many soil concepts reached their change point almost 40 years or more after appearing in all journals (C-A in Table 7). However, change points for soil quality, soil health, and soil care came almost immediately after the soil science journals published articles with those soil concepts (C-B in Table 7).

The number of publications for each soil concept overall increased over time, particularly since 1990 (Figure 1). Soil concepts differed in the speeds at which their publication rates increased. Most journals experienced visibly upward trends in publications up to 2018, except for soil care.

**Table 7.** Exploratory analysis of soil concepts based on inflection points and time of appearance in the all-journal category and soil science journals.

| Soil Concepts | First Appearance (Year) | | Change Point C (Year) | B-A (Years) | C-A (Years) | C-B (Years) |
|---|---|---|---|---|---|---|
| | All (A) | Soil Science (B) | | | | |
| Soil Fertility | 1908 | 1917 | 1971 | 9 | 63 | 54 |
| Soil Productivity | 1910 | 1948 | 1981 | 38 | 71 | 33 |
| Soil Conservation | 1926 | 1947 | 1967 | 21 | 41 | 20 |
| Soil Quality | 1939 | 1971 | 1979 | 32 | 40 | 8 |
| Soil Health | 1951 | 1992 | 1992 | 41 | 41 | 0 |
| Soil Protection | 1953 | 1974 | 1991 | 21 | 38 | 17 |
| Soil Care | 1972 | 1994 | 1994 | 22 | 22 | 0 |
| Soil Security | 1985 | 2013 | 2013 | 28 | 28 | 0 |
| Soil Sustainability | 1992 | 1992 | 1992 | 0 | 0 | 0 |
| Soil Resilience | 1993 | 1993 | 1993 | 0 | 0 | 0 |

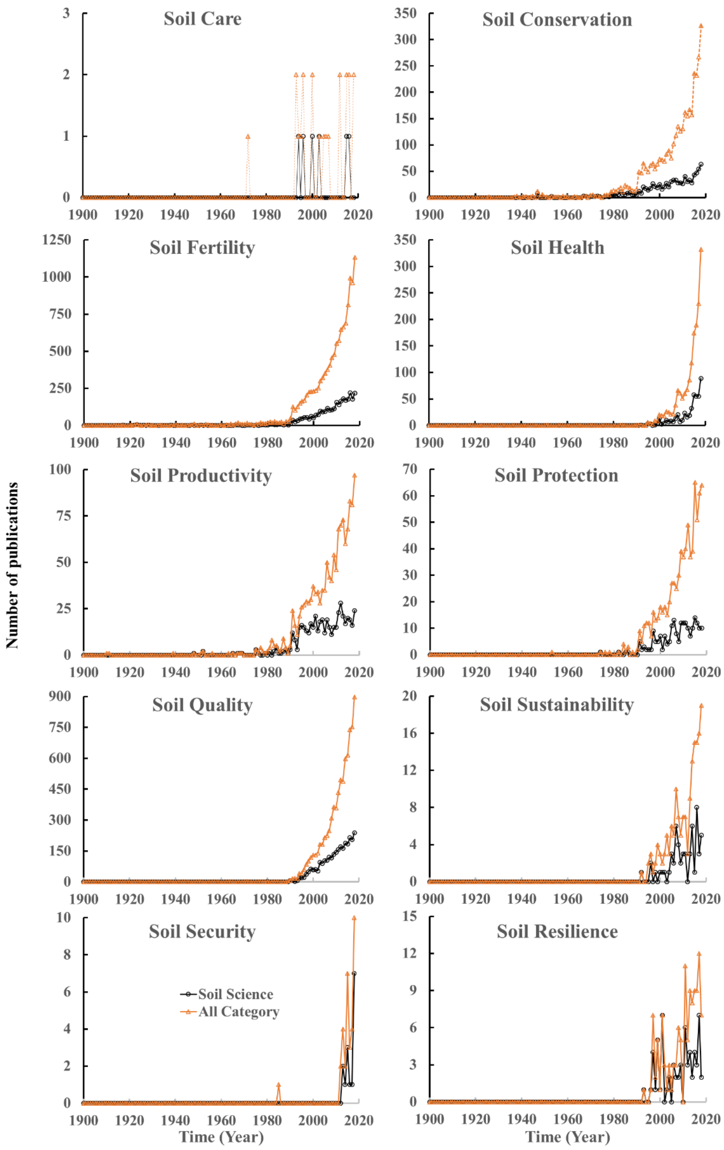


**Figure 1.** Number of publications citing the 10 different pre-selected soil concepts over time from soil science journals (black circles with a solid black line) and all journals (orange triangle with a dashed orange line) available on the Web of Science.

## 4. Discussion

### 4.1. The Emergence of Soil Concepts

Many soil concepts have emerged at different times over the years. The soil fertility concept appeared to be the earliest of all of the soil concepts examined in both all journals (1908) and soil science journals (1917) (Tables 4 and 5). Viets (1977) argued that much of the research that contributed to progress in soil fertility research was conducted even before the establishment of a formalized soil science [21]. McNeill and Winiwarter (2004) supported this idea and asserted that the oldest writing on the topic—the book *Yugong*, which described the characteristics of soil fertility in Northern China—appeared in around 500 B.C.E. [22].

The soil fertility concept has a strong association with measurements of soil nutrients for crop production [23]. Patzel (2004) found the historical linkage between human fertility and soil fertility in the writing—*Mother Earth* [24,25]. The linkage has been developed across diverse cultures as farmers developed a general agronomic theory in the late 18$^{th}$ century [26]. Social and technological development and understanding have also impacted the development of soil concepts. Food supply shortages during and after the World Wars led questions of soil fertility to be central [22] at a time when urgent demand for farm products and high prices confronted U.S. farmers [27]. Many countries in Europe also recognized the need to increase agricultural production, especially after World War II [28]. Justus von Liebig and John Lawes were early scientists in Europe who contributed to the initial development of organic chemistry for soils and mineral fertilizer production, which revolutionized agricultural production. A German chemist, Fritz Haber, later synthesized and industrialized nitrogen fertilizers, which coincided with trends to industrialize and corporatize agriculture and forest industries (e.g., machinery- and technology-derived agricultural revolutions). Land reform after World War II, enforced by U.S. occupation forces, also played an essential role in consolidating fragmented agricultural land in Japan [29]. Other countries in South Asia have increased external inputs to enhance agricultural production by diversifying biophysical and chemical conditions. Soil fertility currently emphasizes the biological, chemical, and physical soil attributes important for provisioning crop nutrients and water [30,31]. The measurements and analysis of such soil properties have been explored as well in context of soil fertility studies, e.g., [32,33].

The concepts of soil conservation and soil productivity appeared in soil science journals at almost the same time in the late 1940s (Table 4). The first author found in the search process for all journals in the Web of Science was Lipman (1926), who argued that soil conservation should deal with both plant-food ingredients and the ability of the soil to attain maximum crop production capability under all environmental conditions [34]. The change point for the soil conservation concept came about 20 years later with Hopp and Slater's (1948) article, published in SS [35]. Hornbeck (2012) reported that many U.S. Plains areas had cumulatively lost more than 75% of their original topsoil due to deep plowing and drought, which was notably visible by the 1940s [36]. Bennett (1974), argued that the origin of the U.S. national soil conservation program occurred much earlier than the U.S. Dust Bowl era of the 1930s [37]. The author stated that an article he wrote, which was published by the Department of Agriculture in the 1920s, was the first comprehensive appraisal of the erosion issue in the U.S. Many regional erosion stations were built and thousands of soil and water measurements were performed to comply with the Buchanan Amendment to the Agricultural Appropriations Bill for 1930. Bennett argued that the commitment of scientists to prevent nutrient runoff and soil erosion was undertaken at the national level using a top-down approach. According to Ice [38], the Soil Conservation Act of 1935, which sought to develop practical methods of managing lands, was the origin of the best management practices (BMPs) of today. Agricultural BMPs were designed to address and minimize agricultural non-point-source pollutions by the applications of excessive fertilizers and pesticides in the U.S. in the 1960s [39]. This movement seems to correspond to the time when R. Carson published the famous book, *Silent Spring*, in 1962. As public concerns for environmental degradations and pollutions had spread, soil conservation also experienced the change point in 1967 (Table 6). From the mid-1960s onward, an increasing number of publications about soil conservation reflected the gradual accumulations of public understanding and awareness.

The enhancement of soil quality was regarded as a goal of improving soil fertility and agricultural productivity through soil conservation [40]. The term "soil quality" appeared in a German soil science journal shortly after articles on soil conservation were published in a non-soil-science journal (Table 4). Wolff (1939) used the term to explain the effect of land use changes on soil characteristics and, in particular, from soil profiling perspectives [41]. The article was published in a German journal that focused on natural sciences [42]. The journal was founded in 1913, and the article was published in Nazi Germany (1933–1941). The vision was to be self-sufficient in producing food for Germans toward World War II that demanded soil assessment (Reichs-Bodenschätzung). This approach to soil assessment could be considered a predecessor to more modern forms of digital soil mapping that emerged in the 1980s [43]. Hans Jenny developed a conceptual model based on the soil-forming factors that were rooted in Vasily V. Dokuchaev's work, and the model became a standard feature of U.S. survey reports in the 1940s and 1950s [44].

The soil quality concept appeared in a soil science journal for the first time 32 years after the term appeared in a non-soil-science journal (Table 7). The article was available as an English translation after being published in the SSS-USSR by Taychinov (1971) [45]. The author used the term to describe the fundamental physicochemical, biological, and hydrological properties of soils as those attributes relate to productivity for agriculture, economic benefits, profitability, and production costs. The definitions/scopes/aims of soil quality were revisited by various authors [2,46–49]. According to Karlen et al. (2001), the concept of soil quality was introduced in the North American literature after the mid-1980s, which was immediately after the concept's change point in the number of publications over time (Table 7) [50]. This may mean that the definition was initially overlooked or not used in North America. A review of soil quality by Bünemann et al. (2018) shows that the broader definition considered soil productivity for agriculture as well as the quality of the environment and animal and human health [31]. The authors argued that the term "soil quality" was introduced by Mausel (1971) [51]; however, some authors pointed to others, such as Warkentin and Fletcher (1977) [52], as being among the first to introduce the concept [47]. In our opinion, the author initially found in the article search, W. Wolff (1939), introduced the term "soil quality."

The similarity/difference between soil quality and soil health is arguable [31]. In defining the concept of soil quality, Parr et al. (1992) stated that soil quality indices could be used to assess the impact of management practices on human and animal health [53]. Though the appearance of soil health in all journals and soil science journals, as well as the change point, occurred many years later than soil quality, the terms have been used interchangeably. For example, Haberern (1992), whose article appeared in the search result for soil science journals, advocated for a soil health index as a report card to document gains and losses in soil quality [54]. Moebius-Clune et al. (2016) posited that soil quality and soil health could be considered synonymous [55]. Bünemann et al. (2018) suggested that the preferred term depends on the stakeholders (i.e., soil quality for researchers and soil health for farmers), although apparently there are no scientific surveys to validate this argument [56]. Stevens (2018) defined soil health as "a holistic measure of a soil's productivity, resilience, and sustainability [6]". The concept is straightforward in the abstract, yet challenging to define in practice from various viewpoints such as farmers, soil scientists, economists, and policymakers.

Some prominent definitions of soil health and soil quality proposed over the past 20 years were summarized and compared by Mizuta et al. (2018) [2]. For example, Doran and Safley (1997) defined it as the "continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity; promote the quality of air and water environments; and maintain plant, animal, and human health [57]". The U.S. Department of Agriculture—Natural Resources Conservation

Service (USDA-NRCS) simplified the definition of soil health in relation to soil quality as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans” [58]. Stewart et al. (2018) proposed measuring the dynamic variables that mainly fell within biological, environmental, and agronomic groups that are responsive to soil management, such as cover crop, based on a meta-analysis of 192 unique peer-reviewed papers [59]. These variables include soil respiration, soil aggregate stability, mineralizable nitrogen (N), soil erosion, infiltration, runoff, nutrient leaching, weed control, diseases, soil fauna, microbial indicators, soil $N_2O$ emissions, microbial biomass N, and other soil health indicators. These variables were measured for traditional soil surveys as indicators of soil quality. Instead, new aggregation methods of existing soil information into a comprehensive, sensible, and scientific-sounding index are the focal point of current discussions in the soil science community [5,60]. Thus, soil health must be reconsidered similar to other soil concepts with the purpose of overcoming some limitations of past soil survey efforts, such as inconsistent soil measurement protocols. Under a large umbrella, the concepts of soil quality and soil health share the common goals of multiple stakeholders by targeting sustainable soil resource management under natural and anthropogenic pressures.

The earliest publication on soil sustainability was found in a soil science journal in 1992; one year later, a soil resilience paper appeared. These concepts were the only ones found first in soil science journals (Tables 4 and 5). Considering that the two concepts appeared at almost the same time, they would likely share similar content, target, audiences, and semantic definitions, because they may be used interchangeably. However, A. J. Friend (1992), the author of the first soil sustainability publication available in the Web of Science, claimed differently [61]. The author first defined soil sustainability as the “susceptibility of soil to change under natural or anthropogenic perturbations,” while soil resilience was defined as “soil’s ability to recover to the antecedent state following degradative perturbation or change in land use.” Soil degradation would be the manifestation of a loss of soil sustainability and resilience. The author also argued that soil sustainability was characterized by three aspects, soil stability, soil resilience, and soil quality, all of which can be influenced by soil surface management (e.g., tillage) to a large degree. This view of soil stability and resilience seems to be consistent with other publications as well. For example, Vogel et al. (2018) argued that the stability and resilience of soil are produced by the complex interactions of functional soil attributes. The important question of how to integrate fragmented knowledge on soil processes from various perspectives was addressed in the article [62].

The roots of the resilience concept can be found in ecology [63]. C. S. Holling, whose work was published in 1973, is considered to be the founder of modern ecological resilience by distinguishing ecological and engineering resilience [64]. However, Olsson et al. (2015) argued that the prevalent theory was not integrated with sociology as socio-ecological resilience [65]. This integral development has altered the earlier definition of the ecological resilience by a different view. Specifically, that resilience expresses the achievement of a new state or equilibrium after perturbations.

Ludwig (2018) considered sustainability from a biodiversity perspective and asserted that potential maximum ecological performance (MEP) is the measurable part of soil characteristics for sustainable management [66]. Three ecological stages were delineated in the framework: resistance, resilience, and regime. The threshold between the first two responses to a disturbance of the ecosystem is expressed by effective MEP, while the threshold between the last two is characterized by potential MEP. However, the sustainability framework is often rather holistic. Wu and Wu (2012) organized various indicator frameworks based on social, environmental, economic, and institutional dimensions [67]. The authors introduced hundreds of various indicators that would be aggregated into indices as measures of sustainable development. The measures of soil sustainability and resilience are still open for discussion. New techniques to quantify the functions or capabilities of soils through integration of existing information with communal consensus seem valuable in advancing the monitoring of soil resources for sustainable use.

The soil care concept does not seem to be used often in scientific journal publications. The concept itself has not been discussed deeply, in terms of definitions, conceptual framing, and practical applications. Review papers were not identified in the database. However, the soil care concept may play a role as a foundation of various soil management strategies based on top-down and bottom-up approaches. Yaalon (1996) defined the concept as "the activity of selecting and implementing, locally and regionally, a system of soil and land use management suitable for maintaining and improving soil usefulness and quality for any selected purpose [8]." Yaalon also argued that knowledge on the topic also needs to be discussed deeply, quantified, and organized, similar to other soil concepts such as soil sustainability. However, Krzywoszynska (2019) addressed the act of care beyond ethical and practical commitments of securing matters by introducing attentiveness [7]. Attentiveness was described as a focal point to relational ethics as "attending to the non-human other, of becoming response-able to them" (p. 4). According to the author, this practice of attentiveness fosters ethical expansions and transformations through encounters between humans and non-humans. Forming care networks of interconnected entities whose existence enables the well-being of the primary object of care, soil is necessary. Grunwald (2021) proposed a novel Pluralistic Integral Soil Ethics (PISE) framework of which one of the pillars is soil care [68]. The ethics of soil care (relational ethics) is rooted in cognitive empathy, which is what a person thinks and understands about soils and the environment, and emotional empathy, which is what a person viscerally feels in relation to soils. Purely cognitive empathy provides factual understanding about soils, while emotional empathy is an embodied experience. They both rely on each other to support action, but empathic concern is a necessity to bring forth compassionate actions (e.g., conservation management). In essence, soil care arises from a compassionate lived emotive relationship between carer (person/community) and cared-for (soil/land/nature). It follows that if somebody (or a community) does not care for soil, and attributes less (or no) value to soil compared to other things, soil degradation and loss in soil quality are tolerated. This conception of soil care stands in contrast to earlier definitions by Yaloon and Wallace that are system-oriented and only involve cognitive empathy.

Soil security also experienced its change point almost immediately after soil science journals published articles. This indicates that publishing research on soil concepts in soil science journals may be a key step in enhancing awareness of newly proposed soil concepts, though the soil science community might not acknowledge the value of new ideas for many years. Interestingly, the definition of soil security found in the first article published in a non-soil-science journal differed from the one first published in a soil science journal. Tadanier and Ingles (1985) used the term to refer to a physical feature of soil (i.e., water retention ability) [69], while Bouma and McBratney (2013) used the term to frame soils as a broader term to address environmental issues, defining soil security as the "maintenance or improvement of the world's soil resource so it can provide sufficient food and fiber, fresh water, contribute to energy sustainability and climate stability, maintain biodiversity and overall environmental protection and ecosystem services" [70]. Most of the results for the soil security concept used the holistic definition. The sources of publications for soil security can be found in *Global Soil Security* [71], though the Web of Science did not recognize the book in the database. The first book chapter conceptualized soil security similarly to food and water security, though soil security was not perceived as a global existential challenge by the public as much as the other security concepts were [72]. Bouma and McBratney (2013) proposed the five C dimensions that define soil security: capability, condition, capita, connectivity, and codification [70]. Grunwald et al. (2017) proposed another C, cognizance, as the fundamental factor that binds the other five dimensions [73]. This feature was characterized as ecological awareness that motivates actions that value, care for, and secure limited natural resources. Although all aforementioned soil concepts aim to protect and preserve soils, their underlying motivations and justifications differ widely [68]. Soil quality, soil health, and soil fertility (and possibly soil productivity as well) have a tight linkage to agricultural production systems, in which the values of the concepts are found in optimized management so that they meet the needs of people and, potentially, other organisms. An anthropocentric stance undergirds soil conservation, suggesting that humans control soil/land/nature to provide benefits for people and the environment. Soil sustainability is associated with "good" stewardship for future generations, while the security of soils refers to being free from the risk of losing functionality and goods and services of sustainable environment [10].

*4.2. Factors for Propagating New Ideas in Soil Science*

Overall, many soil concepts appeared in soil science journals 20 years or more after they appeared in non-soil-science journals for the first time. This reflects the soil science community's slow adaptation to new concepts. However, the earlier a soil concept appeared in the first article in the category 'all journal', the earlier the change points occurred in general, except for soil quality and soil health (A and C-A in Table 7). This phenomenon is possibly due to the more recent rapid increase in the number of articles on newer soil concepts (Figure 1). Publishing new soil concepts in soil science journals is essential for the soil science community to recognize and build communal understanding and values though that would not be a sufficient factor. Sharing a new concept with a large general readership would also help the propagation of soil concepts.

Older concepts were generally cited more over time (Table 3, Figure 1). The minimum number of citations necessary to experience a statistical change point of the publications or a citation inflation in soil science journals was 57 (Table 3), while the number for all journals was 119 (Table 3). The readership of journal subscribers/attention/citations has varied by journal over time, though each journal has fixed scopes/aims/definitions and specific readers. Publishing soil concept articles in a journal with a large readership would be the best strategy, or creating a journal based on a given soil concept is another strategy. For instance, the change point for a number of publications on soil conservation occurred the same year that the JSWC published the first articles (Table 7). Out of 798 and 49 journals in all journals and soil science journals, the journal published the most articles on soil conservation.

To enhance attention from soil science communities and beyond, other important factors must be considered. Rogers (2010) proposed the diffusion of innovation theory to explain how and at what rate a new idea or technology spreads in an organization or community [74]. The diffusion approach has been used to evaluate the impact of development programs in agriculture, family planning, public health, and other fields. According to Rogers, there are five elements of a new concept/idea/innovation that will each partly determine whether the adoption or diffusion of a new one will occur: relative advantage, compatibility, complexity, trialability, and observability. These elements are designed to answer some of the same questions raised in this study (e.g., Why do certain innovative ideas spread more quickly than others, and why do others fail?). Relative advantage is the degree to which a new concept is perceived as better or more useful for particular stakeholders. Compatibility is the degree to which a new concept is consistent with or relevant to existing experiences, values, and the needs of stakeholders. Complexity evaluates how easily a new concept is comprehended—that is, the easier the concept is to understand, the more rapidly it can spread. Trialability indicates whether a new idea can be tested repeatedly. The last criterion, observability, ensures that a new concept will produce visible results.

The first three elements of the diffusion theory are essential to improve the adaptability of new ideas for various stakeholders. For example, the choice of wording may draw different associations and intuitions that could track the attention of stakeholders. Puig de la Bellacasa (2015) stated that soil care is a widely used notion, though the publication result for this concept was relatively low [75]. The term soil care has been associated with intimate relationships, nurturing motherly care (for something or somebody), qualitative values (e.g., long-term sustainability to secure our children's future), and the feminine, which have been devalued in the sciences and overpowered in societies attuned to profitability (e.g., maximize crop production from soil), achievement (e.g., maximize soil carbon sequestration), power, and doing-orientation (e.g., manage and control soils, production agriculture, or "fix the soil degradation crisis"). More discussions on the soil care concept can be found in Grunwald (2021) [68].

Earlier concepts of soil, on the other hand, seem to be limited to agricultural perspectives but were cited in many publications. Multiple factors explain the propagation of new ideas in a community, including needs (e.g., soil degradation); crises/problems (e.g., the Dust Bowl, global climate change); curiosity; psychological (e.g., spiritual or inner motivation to use specific soil concepts); and social (tribal patterns, e.g., scientists may feel inclined to study soil health because their colleagues study soil health).

Social and environmental changes, along with technological advancements and public awareness regarding the need for poverty reduction and sustainable management of natural resources, have impacted public or professional organizations and soil science. Trends in science can shift over time based on the interests of scientists and funding agencies [76]. The prominence of conceptual studies in the literature reflects a given research emphasis and how it has sustained momentum over time.

Soil quality is a good example: it has a clear history of broadening its definition to address complex soil/environmental challenges [31,49]. These conceptual criteria can also be found in the assessments of various soil concept indices. For example, Karlen et al. (1997) asserted that the critical characteristics of a soil quality framework should be that it is (1) influential for the purpose of the assessment (i.e., relative advantage); (2) measurable (i.e., trialability/observability); and (3) sensitive to detect differences at the point scale in time and space (i.e., compatibility) [46]. Doran (2002) proposed that the important criteria for soil quality/health indices are (1) utility and accessibility for agricultural specialists, producers, conservationists, and policymakers (relative advantage/complexity, trialability, and observability) and (2) sensitivity to management and climatic variations (compatibility) [77].

Despite the conceptual criteria for the adoption or diffusion of a new concept, this study offers practical viewpoints for propagating awareness of soil concepts. The choice of journals in which to publish articles on a soil concept influences the citation trend of soil concepts. The large audience/readership outside of the soil science communities needs to be considered because 63% of the citations for the soil concepts selected for this study were from non-soil-science journals. The united efforts of professional organizations/institutes within a country are also valued. It is notable that publication sizes for authors in the Chinese Academy of Science (CAS) for many soil concepts were the largest, including soil conservation, fertility, productivity, quality, and sustainability. This observation may be linked to a large number of scientists from 114 institutions under the CAS, which is the world's largest research organization recognized by Nature Index [78]. However, one might claim that this is not a fair comparison because many countries, including the U.S., have not adopted the scheme that the Chinese have. Collaborations across nations or people who speak different native languages is another factor in determining scientific awareness as a part of cultural adaptability. The most prominent languages varied depending on the soil concept, but the least cited concepts—soil care and soil security—were only published in English. Efforts by a single organization (i.e., the University of Sydney) contributed the majority of publications on soil security in all journals (39.4%) and soil science journals (46.7%), which indicates the monopolization. However, opposite trends were found for other soil concepts that showed pronounced diversification in the form of English/non-English publications indicating cultural and social adaptability.

A cultural or typological aspect may play an important role in restricting citations. Lal (1993) referred to soil resilience as "soil's ability to recover to the antecedent state following degradative perturbation or change in land use" [20]. However, Olsson et al. (2015) argued that the use of the term "resilience" in the natural sciences may cause disciplinary tensions with the social sciences [65]. The application of resilience theory may change the definition from coherent to internally contradictory, from precise to vague, from descriptive to normative to predictive, and from concise to comprehensive. Sojka et al. (2003) also warned that the vague quality of assessments requires deconstruction for interpretation [9]. Expanding stakeholders by broadening soil concepts may succeed in considering diverse stakeholders and functions of soils, but it also seems to be a tradeoff with the possibility of losing the capability for scientific advancement. Furthermore, vagueness can confuse readers/users, and, as a result, divisions within soil science might be created. Soil quality and soil health are good examples because these are interchangeably used depending on the author.

### *4.3. Limitations of This Research and Future Research*

Some limitations of the study can be opportunities for future research. Some articles originally written in German were identified in the English translation, so articles in original languages other than English might not be as readily accessible to readers in the Web of Science. Adding other sources, such as Google Scholar, may retrieve soil concept articles unavailable in the Web of Science.

In addition, different search settings may produce different results for total citations for all journals and soil science journals. The wildcard character and quotation marks were used to identify exact phrases of soil concepts with slight flexibility in plurality (e.g., soil care and soil cares). However, some articles—for instance, the paper titled "Soil structure and sustainability" [79]—were not counted in the total citations for soil sustainability in all journals. Thus, expanding searchability may increase the chance of finding unidentified articles published earlier than those found in this study.

## 5. Conclusions

Soil concepts have emerged at different times, often changing in the frequency of their use and their meanings over time. Whether soil concepts persist, are replaced, diffuse, or make room for new ones reflects real societal needs and improved scientific understanding. However, soil scientists may require decades of time and a significant number of publications published in soil and non-soil-science journals to adopt new ideas within the soil science community. The increasing number of citations in both the short- and long-term also requires the expansion of audience/stakeholders in different countries/organizations, including those who use languages other than English or Chinese as their primary language. While not every soil concept has attracted widespread interest, those cited more than 50 times in the soil science journals have tended to acquire momentum, communal value, and understanding in diverse communities. Establishing new concepts with a lack of novel semantics inherently risks creating communication barriers between scientists and other stakeholders, specifically if those concepts are regarded as scientific buzzwords and/or jargon. Older soil concepts that emerged in soil science journals in the early 1900s apparently related to agriculture and productivity. The newer concepts developed since the 1970s address management, functionality (e.g., soil security and soil health), and biocentric themes (e.g., soil resilience). Within the semantic field, it seems that the original meaning of a specific soil concept at emergence relaxes and broadens over time, with research publications diverting from the original definition. This phenomenon is exemplified by the concept of soil health, with exponentially growing publications over the past decade but a loss of clear and precise semantics of the term soil health.

The definition of each concept has been modified over time, depending on external crises in society/environment (e.g., global climate change, food security) and/or internal interests within the soil science community. The soil concepts that are successfully popularized will likely be impacted in the future by shifts from disciplinary soil-centered research toward more inter- and trans-disciplinary environmental research as global ecological and humanitarian crises intensify.

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